

THEORETICAL STUDIES OF TIME DEPENDENT/INDEPENDENT RADIATIVE TRANSFER INCLUDING INELASTIC SCATTERING FOR BOTH ACTIVE AND PASSIVE SOURCES

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LONG-TERM GOALS

Long term goals are to obtain a thorough understanding of the behavior of the complete Stokes vector both within the ocean and in the atmosphere as well for both elastic and inelastic scattering for both active and passive sources. Specifically, we want to see how one can use polarization information to obtain more information about the IOP's of both oceanic and littoral zone constituents. We also want to explore the efficacy of polarimetric time-of-flight lidar techniques in determining salinity and speed of sound in the ocean as well as submersible object detection. We want to continue our collaborative program in ocean polarimetry with the group in Minsk headed by Dr. Eleonora Zege.

OBJECTIVES

It is our major objective to find new and innovative ways in which polarimetry can be used to determine not only inherent optical properties but also certain physical properties such as temperature and salinity of ocean water.

We also would like to explore the possibility of using Raman circular depolarization techniques to determine temperature and salinity as a function of depth. This information will be invaluable in speed of sound determination and will also be useful to physical oceanographers who need accurate density data for ocean models.

We have begun a collaborative program with the Radiative transfer group in Minsk, Belarus headed by Dr. Eleonora Zege. Our combined objectives for this program are as follows:

- a) Simplification of the equations for the elements of the Green's matrix for the VRTE. Development and testing of an algorithm and code to compute the Stokes vector in an atmosphere-ocean using the Multicomponent approach (SVM-code).
- b) Computation of the polarization characteristics of the light field in the ocean and atmosphere under solar illumination employing Monte-Carlo and SVM codes. Comparison of results and Elucidation of ways to improve both codes.
- c). Development of the simplified equations for propagation of a linearly polarized beam in order to study the Stokes vector in the on-axis region for both backward and forward directions.
- d) Development of the code to compute the Stokes vector in the on-axis region for a polarized narrow beam and compare with experimental data.
- e) Improving the codes for computation of the polarization characteristics of the light field in the ocean and atmosphere under solar illumination. Computation via improved codes. Data comparison.

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APPROACH

We have developed some very sophisticated Monte Carlo codes to handle the following types of problems:

- a) Complete Stokes vector calculations for a passive source(the sun) illuminating a plane parallel inhomogeneous atmosphere-ocean system with a wind ruffled dielectric interface.
- b) Development of a sophisticated Monte Carlo code that utilizes a new idea we have developed which uses convolution theory to evolve the frequency profile of multiply scattered photons to handle both Raman and Brillouin scattering.
- c) We have developed a higher resolution Monte Carlo code for studying the finer structure in the polarization state of scattered light in an atmosphere-ocean system. Using our bulk Monte Carlo codes which solve the complete polarized equation of transfer for the full observable solid angle at any height above or below the ocean surface we are able to isolate regions of interest and to then apply our Monte Carlo with estimation techniques to these smaller areas.
- d) We have also applied estimation techniques to the observation of polarization anisotropy in the backscattered light of a laser beam incident on a solution of Mie type scatterers. Our Monte Carlo code has produced images capturing all the qualitative features of observed phenomena so far reported in the literature. Our analysis shows that it may be possible to remotely determine particle sizes and concentrations by use of a system of polarizing analyzers and an active laser source. In the development of our code we have also shown that circularly polarized light has a longer "memory" of its initial polarization state than linearly polarized light and reflects interesting characteristics of the scattering medium. This persistence of circular polarization suggests that circularly polarized sources will allow observers to determine the characteristics of scattering particles deeper in the ocean than is possible with linearly polarized sources.

WORK COMPLETED

- a) We have used our multiple scattering inelastic scalar radiative code with unique handling of the photon frequency distribution in order to investigate multiple scattering effects on the lidar return signal in a medium where both Raman and Brillouin scattering are taken into account. A paper on this study has now appeared¹.
 - b) A study of neutral points in the upwelling light field in an atmosphere-ocean system has been completed and a paper on this study has now appeared².
- Haltrin and Dr. Alan Weidemann at NRL Stennis Space Center has been completed and published³
- d) One phase of a collaborative project with Dr. Neils Hjerslev and Dr. Eyvind Aas has been completed. This project involved a comparison of data taken in the Mediterranean in 1971 of the radiance and degree of polarization with Monte Carlo models. A paper is presently being prepared on this research project.
 - e) One phase of our study of the polarization patterns produced by the scattering of a laser beam from a highly scattering medium has been completed using Monte Carlo techniques⁴. A theoretical analysis

using incoherent double scattering theory has also been carried out and we have shown that the patterns observed experimentally can be accurately emulated. A manuscript on this research has already been submitted to Applied Optics⁵.

RESULTS

We have shown that even an effectively crude hydrosol model can be used to generate a single scattering Mueller matrix which can be used to model the degree of linear polarization which agrees quite well with polarization data taken in the Mediterranean in 1971. To understand the notation in the comparison figure, the reader is referred to Fig. 1 which shows the geometry of the measuring device.

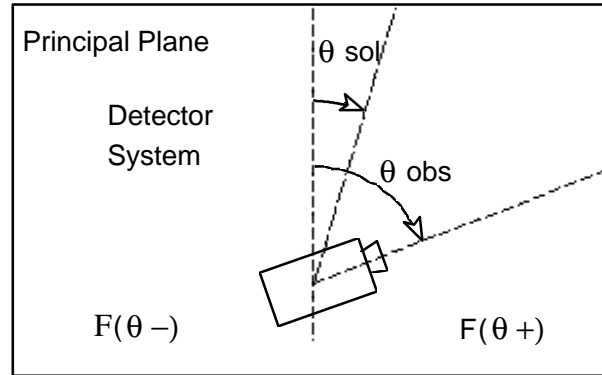


Fig. 1 Geometry of the detector system used by Hjerslev and Lundgren to record the radiance and polarization data taken during a Mediterranean cruise in 1971. θ_{sol} is the incoming solar zenith angle and θ_{obs} is the angle of observation of the detector.

In Fig. 2 we show a comparison of the Monte Carlo emulations and the experimental data. In this figure we compare radiance, $L(\Theta)$ (upper graph) and degree of polarization, $P(\Theta)$ (lower graph) in the principal plane computed with our Monte Carlo model with measurements taken in the Mediterranean by Hjerslev and Lundgren at a depth of 25 m with an average solar zenith angle of 29° . Two different phase functions were used in the emulations; namely, a Petzold phase function and the other from measurements taken by Kullenberg in the Mediterranean. The other elements of the Mueller matrix remained unchanged and were generated from Mie theory and due to the small relative refractive index placed the calculations in the Rayleigh-Gans regime. It is interesting to note that even though the radiance agrees quite well, the polarization shows some deviations in certain regions. In light of the fact that no atmospheric conditions were noted at the time of measurement, the agreement is quite remarkable.

We have also been able to successfully show that the polarization patterns observed by Pal and Carswell⁶ resulting from scattering a laser beam off of clouds or a suspension of polystyrene spheres can be accurately modeled by using incoherent scattering theory. Other researchers⁷ have claimed that the use of coherent scattering is necessary to explain these polarization patterns.

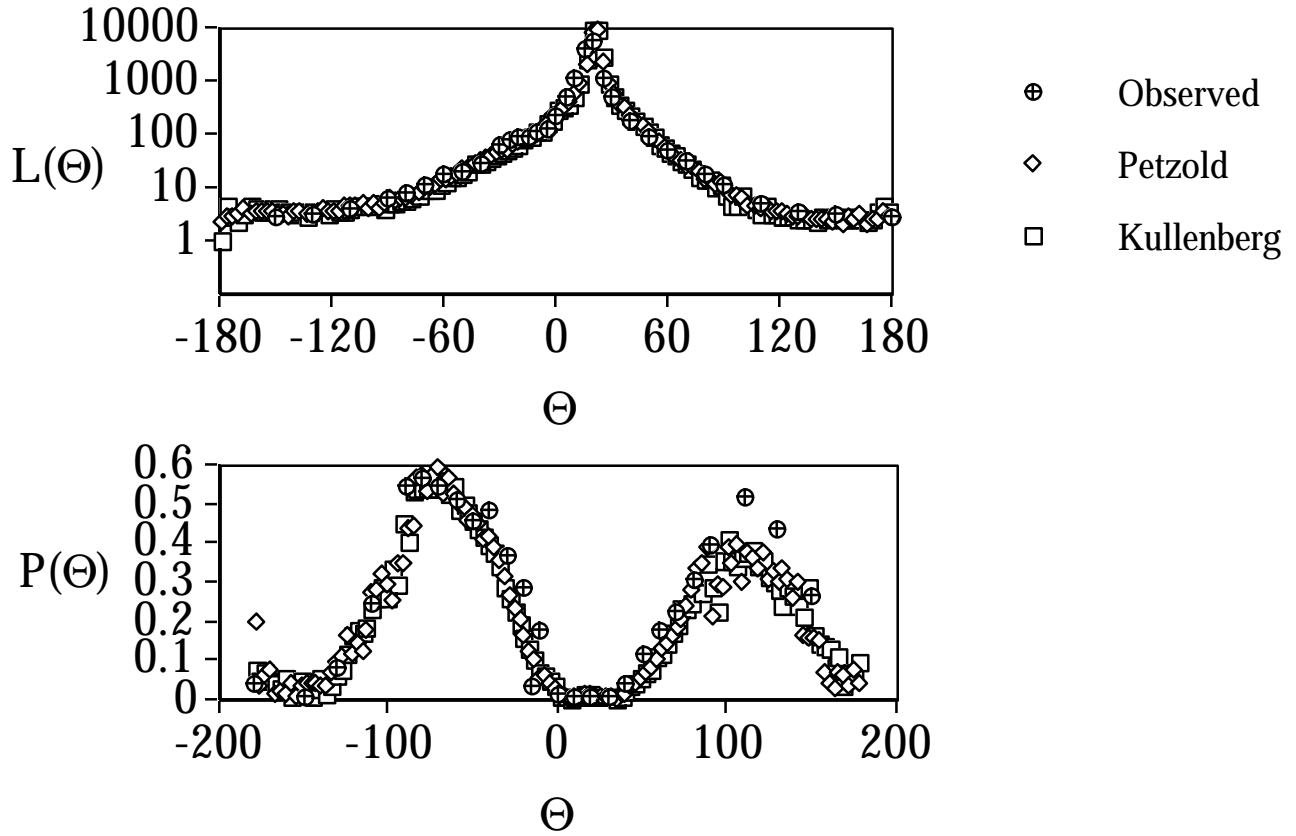


Fig. 2 Radiance (upper graph) and polarization (lower graph) comparison. The observed data points were taken by Hørslev and Lundgren in the Mediterranean at a depth of 25 m. The Monte Carlo emulations used both a Petzold and a Kullenberg phase function. The solar zenith angle was 29° .

IMPACT/APPLICATION

These studies give more credence to the versatility of polarimetric methods for determining IOP's from AOP's for both deep ocean and littoral zone waters for both active and passive sources. We hope to see complete Stokes vector measurements as commonplace as radiance measurements in the next few years.

Our Monte Carlo programs for laser scattering from turbid media are presently being used to study light scattering from living tissue. We feel that polarimetric techniques may be useful in detecting precancerous skin lesions.

We feel that polarization spectroscopy in the ocean may be a way to extract both temperature and salinity profiles in the ocean.

TRANSITIONS

Our Monte Carlo passive source Stokes vector programs are being used to check a different method for solving the equations of transfer with full Stokes vector treatment developed by Dr. Eleonora Zege and her group in Minsk, Belarus. We have a CRDF grant for this work

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